The Effect of Speed and Body Weight Support on the Ankle-Foot Roll-Over Shape

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Abstract

Body weight supported treadmill training (BSWTT) is a method of gait rehabilitation for neurological injuries such as incomplete spinal cord injury and stroke. During this therapy, patients placed over a treadmill have a portion of their body weight supported with a harness, and trained therapists provide manual assistance as necessary to promote upright posture and lower-extremity trajectories associated with normal gait. Despite its prevalence, much is still unknown about the effects on gait of key BWSTT parameters, such as treadmill speed and the percentage of body weight support (BWS).

Successful rehabilitation with BWSTT depends on accurately replicating the forces and motions present during normal locomotion. A single measure that expresses the relationship between these terms is the ankle-foot (AF) roll-over shape, defined as the circular arc formed when the center of pressure (COP) is transformed into a shank-based coordinate system. This shape is suggested to be clinically invariant under a variety of walking conditions. Thus, changes in the AF roll-over shape with BWS may indicate that the relationship between the forces and motions associated with normal walking is altered during BWSTT. This study seeks to determine the effect of BWS on the radius of the AF roll-over shape and the anterior location of its center.

We tested seven subjects on an instrumented treadmill at 3 speeds (50%, 100%, and 150% of a self-selected speed) and with a harness providing 4 levels of body weight support (0%, 30%, 50%, and 70% of the subject's weight). We found that, contrary to the previously found invariance of the AF roll-over shape, the shape did change with speed, body weight support, and the interaction between the two. This variability was most pronounced at the highest levels of speed and body weight support. Thus, the ankle-foot roll-over shape may not be an invariant metric when BWS is applied.

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1. Introduction

Spinal cord injury (SCI) affects hundreds of thousands of people in the United States with an estimated incidence of 12,000 new injuries per year (UAB, 2008). The average age at which these injuries are sustained is 39.5 years, which means that the injury has occurred early in life (UAB, 2008).

An SCI affects motor and sensory function below the level of the injury (Trieschmann, 1988). The location of the injury determines which functions are affected. As seen in Figure 1.1, a certain spinal cord region provides primary control for each area in the body. An SCI affects all areas of the spinal column inferior to the location of the injury. This injury can be classified as one of two levels of severity. An individual with an incomplete lesion retains some level of motor or sensory function below the level of the injury. However, an individual with a complete lesion will lose all such motor and sensory function.

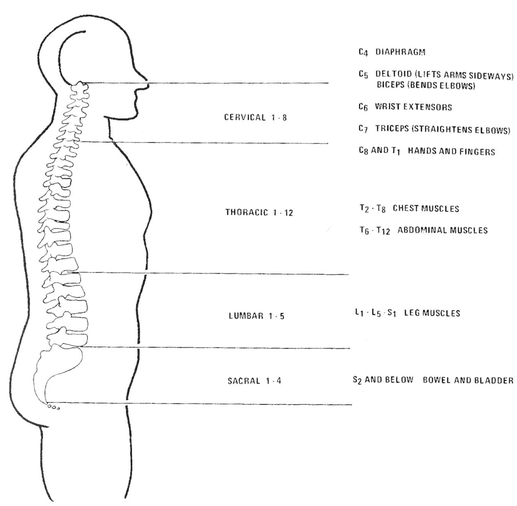


Figure 1.1: Areas of the body controlled by different portions of the spinal column (Trieschmann, 1988)

The lumbar region controls the legs and, as is seen in the diagram is likely below the level of injury

Since the legs are controlled by the lumbar region of the spine, which is one of the most inferior portions of the spinal column, SCI usually results in either lost or impaired locomotion. This loss greatly limits the ability of SCI patients to resume normal activity. Those with SCI are frequently depressed and unsatisfied with their lives, and the inability to walk contributes to this dissatisfaction (Anderson, 2004). These patients desire to regain an independent lifestyle in which they can interact with their environment as normally as possible. Therefore, there is a need for a rehabilitation method that retrains these individuals to be able to walk.

Body Weight Supported Treadmill Training (BWSTT) emerged in the 1980s as a rehabilitation strategy to help SCI patients with an incomplete lesion regain the ability to walk (Barbeau et al., 1987). BWSTT for SCI rehabilitation is an activity-based therapy that aims to help patients recover neural control of locomotion. The patients perform stepping motions while their body weight is partially supported with a harness. Clinicians assist patients with their balance and generating the stepping motions as necessary. The level of motor control retained by the patient, as well as the level of spasticity, or persistent involuntary muscle contraction, impacts the degree of assistance required to produce normal walking patterns. Both a schematic representation of the BWSTT setup and a picture of a patient undergoing BWSTT may be seen below in Figure 1.2.

a) 

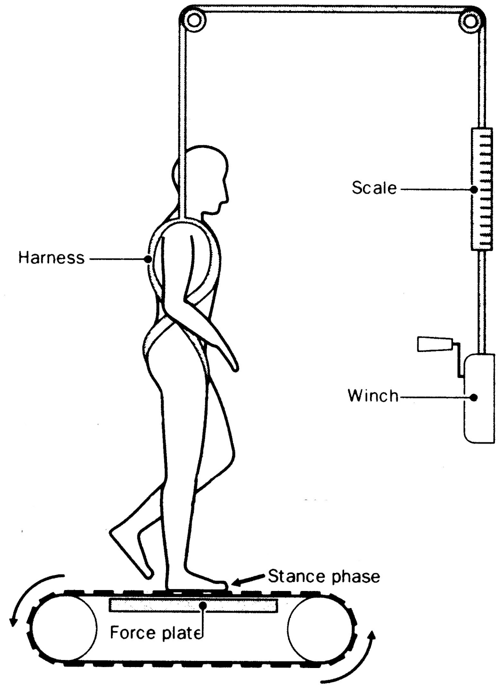
b) 

Figure 1.2: a) A patient undergoing BWSTT (Photo courtesy of www.dispatch.com), b) A schematic of the BWSTT system (Van de Crommert et al., 1998)
Picture (a) shows a patient in the NeuroRecovery Network during BWSTT, while (b) shows a schematic of an example BWSTT system. Our system uses pneumatic closed-loop control rather than a winch and scale.

The central pattern generator (CPG) is one basis for this training. The CPG is believed to be a network of neurons in the spinal cord responsible for creating the rhythmic motion of walking. These rhythmic patterns are shaped by load and position feedback from low threshold cutaneous afferents and extensor muscle afferents, respectively, creating the closed-loop system seen in Figure 1.3 (Duysens and Van de Crommert, 1998). While there is limited evidence supporting the existence of the CPG in humans and other primates compared to other vertebrates such as cats, observations of SCI patients support the notion of a CPG in humans (Duysens and Van de Crommert, 1998). It is believed that BWSTT reactivates the CPG to produce improvements in locomotion (Van de Crommert et al., 1998).

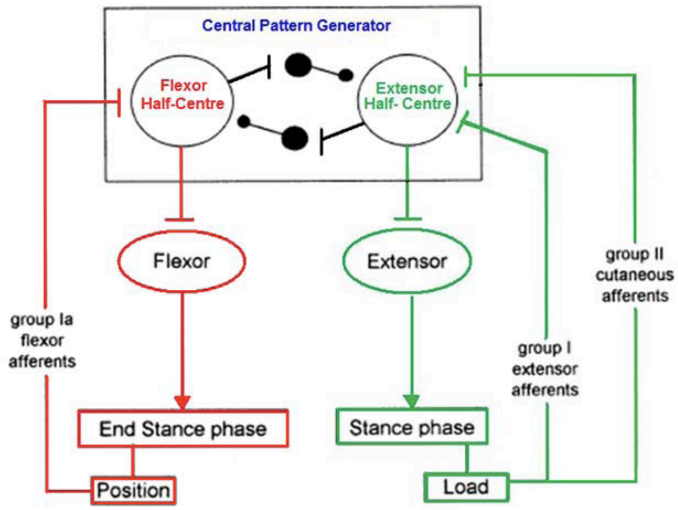


Figure 1.3: Diagram of CPG Feedback System

The CPG relies on feedback from flexor and extensor muscle afferents (group Ia and group I, respectively) and low threshold, group II cutaneous afferents to shape the rhythmic patterns associated with walking. Figure adapted from (Van de Crommert et al., 1998).

Around 76% of SCI patients with incomplete lesions who undergo BWSTT regain independent locomotion (Van de Crommert et al., 1998). However, even after training, many individuals present gait abnormalities, including decreased dorsiflexion and trunk control (Finch et al., 1991). In order for BWSTT to be effective, both the forces and movements exhibited during gait must be replicated during training (Hutchinson et al., 2004). This requirement may be the result of the need to provide appropriate afferent feedback for proper tuning of the patterns generated by the CPG (Van de Crommert et al., 1998). However, two parameters of BWSTT that have the potential to affect the afferent feedback that is the key to the CPG, the speed of the treadmill and the level of body weight support (BWS), are currently set by the therapists based on what "looks right" to the therapists administering the rehabilitation. This arbitrary way of setting the speed of the treadmill and percentage of BWS results in wide variability in training parameters with no consensus as to appropriate speed and BWS levels (Hidler, 2005). The variability in BWS and speed leads to questions regarding the effect these parameters have on the effectiveness of the training, such as whether the gait of the patient is changed when these parameters are adjusted. Therefore, levels of speed and body weight support that do not allow for appropriate afferent feedback may be a contributing factor in the cases where patients do not regain normal, independent locomotion.

Due to the complex physical and neurological systems involved in locomotion, it is desirable to have a simple metric by which to look at the forces and motions during locomotion. Previous research has suggested that the systems involved in locomotion coordinate to produce accurate foot trajectory (Ivanenko et al., 2003), so such a metric might focus on the interaction between the foot and the ground. The ankle-foot roll-over shape is a metric combines that forces and motions in a model that focuses on foot contact. The ankle-foot roll-over shape combines the foot and ankle into one rocker-like shape to model limb kinematics between ipsilateral and contralateral heel strike, based on the rocker-based inverted pendulum theory of walking. This shape is derived from the movement of the center of pressure (COP) in the sagittal plane as an individual walks. If observed from a global coordinate system**,** the COP appears to move linearly across the ground. However, if observed from a coordinate system attached to the shank, the COP appears to move in a circular arc (Hansen et al., 2004). (Figure 1.4, Figure 1.5)

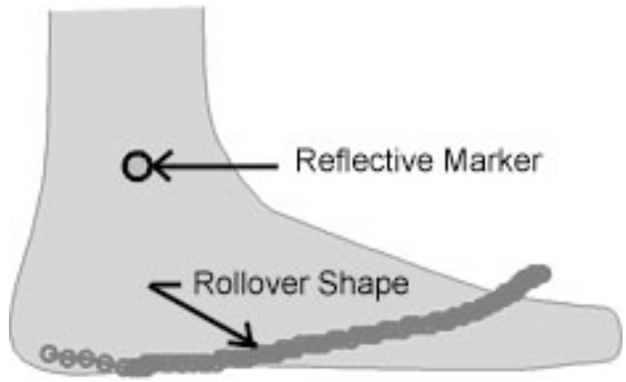


Figure 1.4: Schematic of the ankle-foot roll-over shape
When transformed into a shank-based coordinate system, the center of pressure appears to move in a circular arc known as the roll-over shape. Adapted from (Hansen et al., 2004)

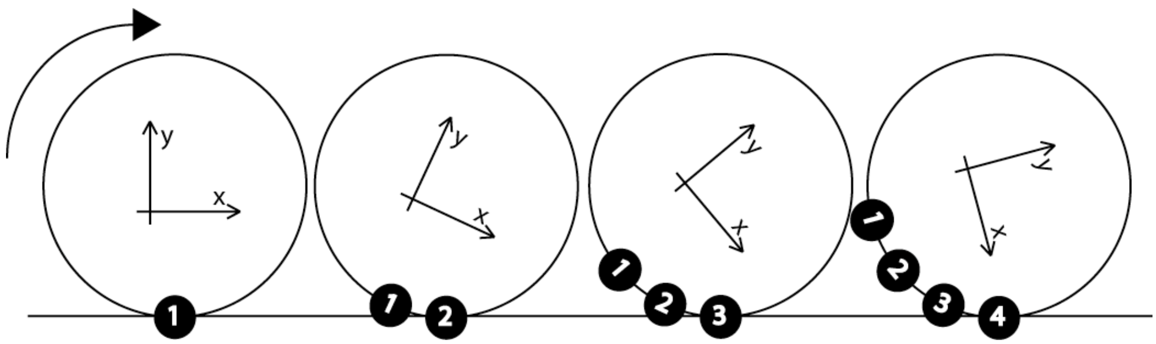


Figure 1.5: Rolling wheel analog for the ankle-foot roll-over shape
From the global coordinate system it appears that points 1-4 move linearly along the ground. However, from the coordinate system attached to the rolling wheel it appears that points 1-4 move in an arc along the circumference of the wheel. Similarly, from a coordinate system attached to the shank, the center of pressure appears to move in an arc along the effective rocker of the person's gait. Adapted from (Hansen et al., 2004)

This simple model allows the complex process of locomotion to be considered in terms of the two characteristic variables of the ankle-foot roll-over shape: the radius of this arc and the location of its center. Hansen and colleagues found the ankle-foot roll-over shape to be clinically invariant for an individual through varied speeds under full weight-bearing conditions (Hansen et al., 2004), varied levels of added weight (Hansen and Childress, 2005), varied inclines (Hansen et al., 2004), and low and medium heel heights (Hansen and Childress, 2004). However, when Hansen and Childress added weight to their subjects, changes in speed did cause the roll-over shape to change statistically, but not clinically, significantly (Hansen and Childress, 2005).

These findings demonstrate the clinical invariance of the ankle-foot roll-over shape under many weight-bearing walking conditions and under added weight, when subjects had full control of their center of mass without external assistance. However, it is unknown how reduced weight, a condition seen during BWSTT, affects the ankle-foot roll-over shape.

1.1 Focus of thesis

This research seeks to determine the effect of BWS and speed on the radius of the ankle-foot roll-over shape and the location of its center. We tested subjects under a variety of speeds and levels of BWS and determined whether the ankle-foot roll-over shape, which has been shown to be clinically invariant under most walking conditions, was invariant when BWS was applied over a range of speeds.

1.2 Significance of Research

This research has significance in the use of BWSTT as a strategy for retraining SCI patients for locomotion, as both speed and BWS are varied during training. Several studies have looked at the ankle-foot roll-over shape (Hansen and Childress, 2004; Hansen et al., 2004; Hansen and Childress, 2005) and suboptimal outcomes with BWSTT (Finch et al., 1991; Van de Crommert et al., 1998)but there is no work that looks at the two in conjunction. Due to the suggested invariance of the roll-over shape in normal walking (Hansen et al., 2004; Hansen et al., 2004; Hansen and Childress, 2005), it may be a valuable tool by which to characterize the effects of body weight support and speed during BWSTT. If the shape is constant with increased speed and BWS, it may be valuable as an objective measure by which to evaluate treadmill training protocols and promote objective procedures to determine training parameters. The use of such an objective metric may result in more consistent training outcomes.

1.3 Overview of Thesis

This thesis contains five chapters. The next section, Chapter 2, discusses the experimental methods. Chapter 3 presents the results of the experiment, which are then discussed in Chapter 4. Chapter 5 contains the conclusion and suggests opportunities for future work related to this research.

2. Experimental Methods

We collected kinematic and kinetic data from 7 neurologically unaffected subjects, 4 male and 3 female. We excluded anyone with recent pain in the back, leg, or foot, anyone who was pregnant, and anyone who was allergic to adhesives. The subjects were an average of 26±8.7 years old and had an average height of 1.74±0.09 meters. We obtained informed consent from each participant before performing the study.

2.1 Equipment and procedure

We collected the data in the NeuroRecovery Network (NRN) in Dodd Hall at the Ohio State University Medical Center (OSUMC). Physical therapists in the NRN use the two functioning BWSTT stations to train their patients, one of which we used to collect our data (Figure 2.1).

Figure 2.1: Body weight supported treadmill training station in the NeuroRecovery Network
We used this station to test subjects. Shown in this picture is the split-belt instrumented treadmill substituted for the center's treadmill that was not instrumented.

At this station, a closed-loop pneumatic force control system (Vigor Equipment, Stevensville, MI; Tescom, Elk River, MN) provided BWS (Figure 2.2). Subjects walked on a split-belt instrumented treadmill (Bertec Corp., Columbus, OH) with force plates under each belt to record ground reaction force (GRF) and COP data (Figure 2.1). We installed seven Vicon motion capture cameras to record kinematic data (Vicon Mx cameras, Vicon, Inc.) (Figure 2.3).

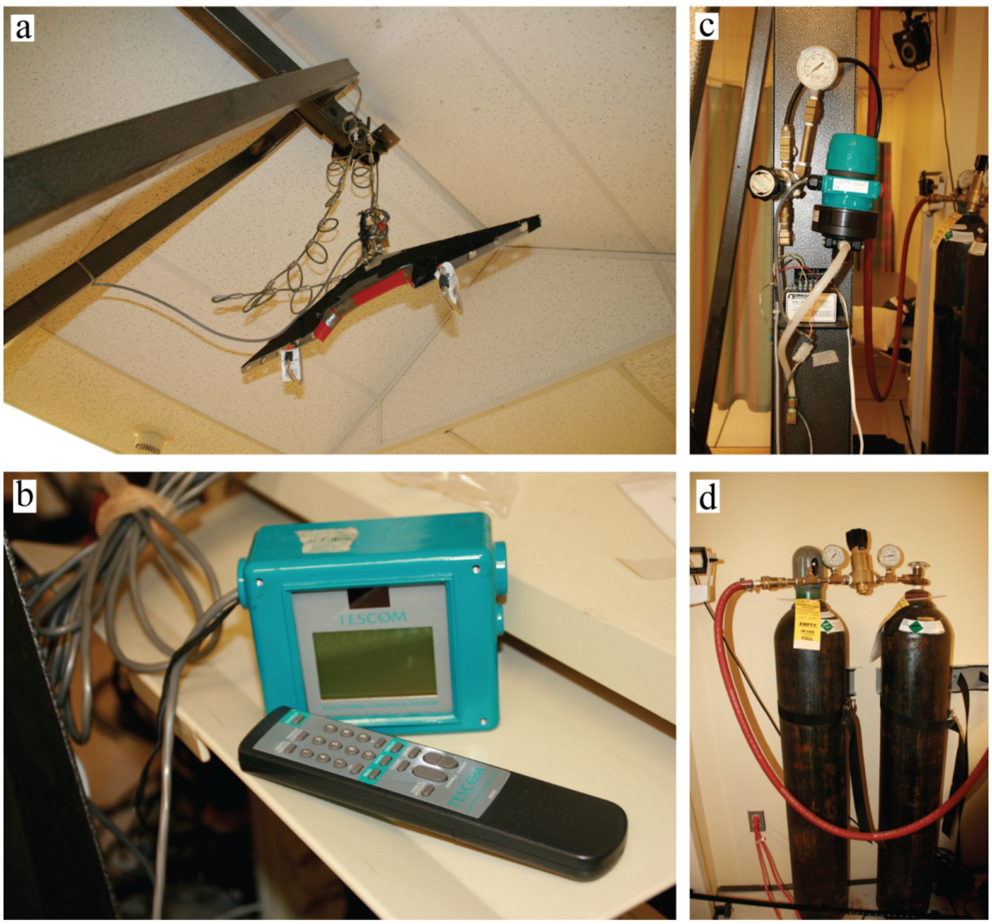


Figure 2.2: Body weight support system

The components of the closed-loop pneumatic system that provided body weight support, including (a) the yoke to which the harness was attached, (b) the control box, (c) the pneumatic control, and (d) supply tanks

Figure 2.3: Vicon motion capture camera

There were seven Vicon motion capture cameras located around the room in order to capture kinematic data

We helped each subject don one of the two-part medical harnesses used by the patients in the NRN. The upper and lower components of the harness supported the torso and pelvis of the subjects, respectively, and were connected by four straps. The BWS system was connected to the upper portion of the harness (Figure 2.4).

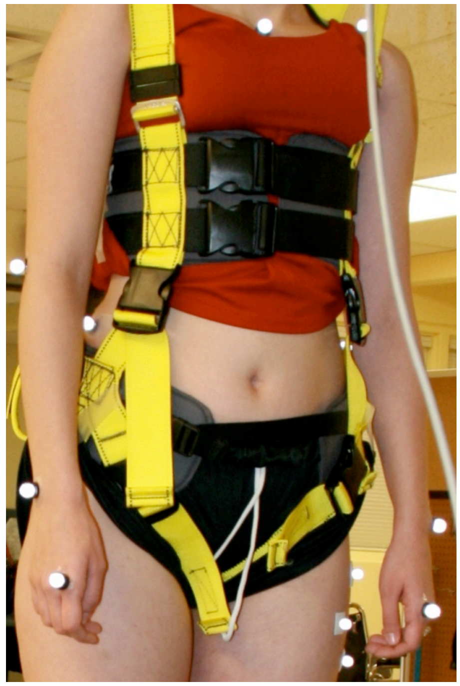


Figure 2.4: Two-part harness used for body weight support

The two-part harness used for body weight support. The bottom portion supported the pelvis and the torso portion was connected to the body weight support yoke. Vertical straps connected the two portions of the harness.

Once the subjects donned the harness, they walked 10 meters overground to determine their casual walking pace. We informed the subjects that we would record their speed and that they would be required to walk at speeds both faster and slower than this casual, or self-selected (SS) speed. We then recorded the subjects' heights and foot lengths.

We applied reflective markers to anatomical landmarks on the subjects using the point-cluster technique (Andriacchi et al., 1998). This study is part of a larger study that used all of the markers. However, for this component, only five of these markers were used: the lateral malleolus, calcaneus, 2nd metatarsal, and lateral epicondyle on the left side and the 2nd metatarsal on the right side (Figure 2.5).

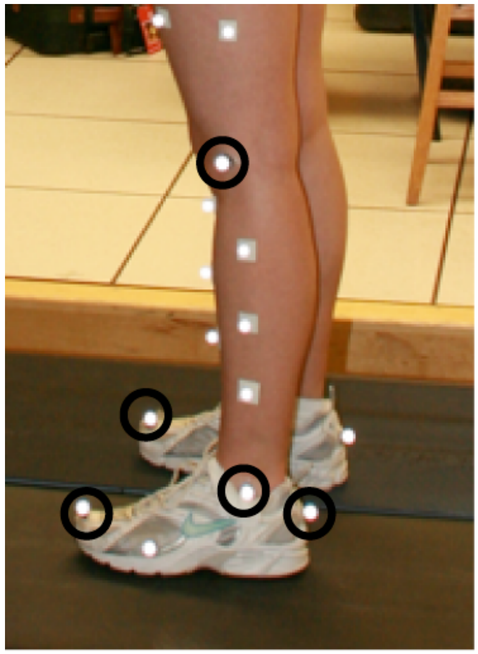


Figure 2.5: Markers used to collect kinematic data.
These five markers (calcaneous, lateral malleolus, 2nd metatarsal, and lateral epicondyle on the left limb and 2nd metatarsal on the right limb) used to find the roll-over shape

After we applied the markers to a subject, we connected the BWS system to the harnesses, and the subject stood quietly on the treadmill for static calibration. Following the static calibration, the subjects practiced walking without BWS at their SS speeds and at the extremes of body weight support and speed that they would experience during the study.

Once the subjects were accommodated to the treadmill and BWS system, they performed 12, 30-second walking trials with a rest period between trials. We recorded COP data for the left side of the body and motion capture data for both sides of the body at 200 Hz during these trials. The subjects' testing conditions were randomized, at three speeds (50%, 100%, and 150% of self-selected speed) and four levels of BWS (0%, 30%, 50%, and 70% of body weight). These conditions were chosen to include the speeds and levels of BWS typically used during rehabilitation (Finch et al., 1991; Dietz et al., 2002)

2.2 Data Analysis

We processed the motion capture data using ViconNexus software. This software allowed us to identify the location of each marker in space and track its path over time. Once the markers were identified, they were fit to a three-dimensional kinematic model of the subjects' motion (Figure 2.6). We used this model and other algorithms in ViconNexus to fill any gaps in marker data and find smooth curves for each marker's trajectory. We selected ten steady-state gait cycles to analyze for each trial from each subject.

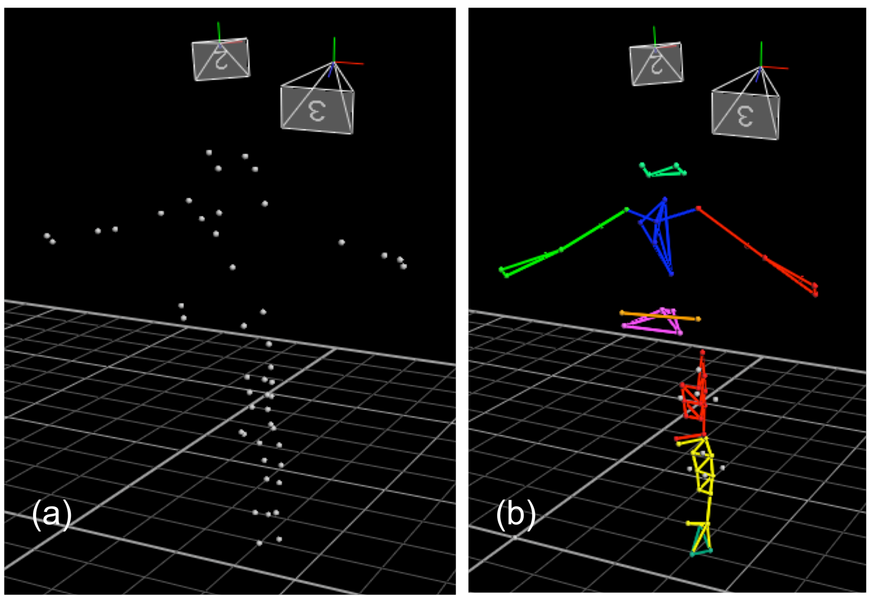


Figure 2.6: Vicon motion capture processing environment

(a) Raw marker set as interpreted in the Vicon Nexus environment. The cameras identify markers and triangulate each marker's position in space. (b) The markers have been assigned to specific anatomical landmarks and divided into functional groups. These groups represent segments in the kinematic model.

Next, we exported the GRF data and COP and marker coordinates from ViconNexus into a comma separated value (.csv) file. Custom MATLAB code (Appendix A) read and processed the data from these files. We isolated the gait cycles from one another using vertical GRF, with the gait cycle beginning and ending at consecutive left heel strikes. From these gait cycles, we again used vertical GRF to isolate the stance phase because the ankle-foot roll-over does not have any meaning when the foot is not in contact with the ground during swing phase.

We created a coordinate system based on the coordinates of the markers representing the lateral malleolus, lateral epicondyle, calcaneous, and 2nd metatarsal. A unit vector along the direction from the lateral malleolus to the lateral epicondyle defined the z-coordinate of this Cartesian system. The cross product between this vector and a unit vector along the position vector from the calcaneous to the 2nd metatarsus defined the y-axis. Finally, we defined the x-axis as the cross-product between these two axes (Figure 2.7).

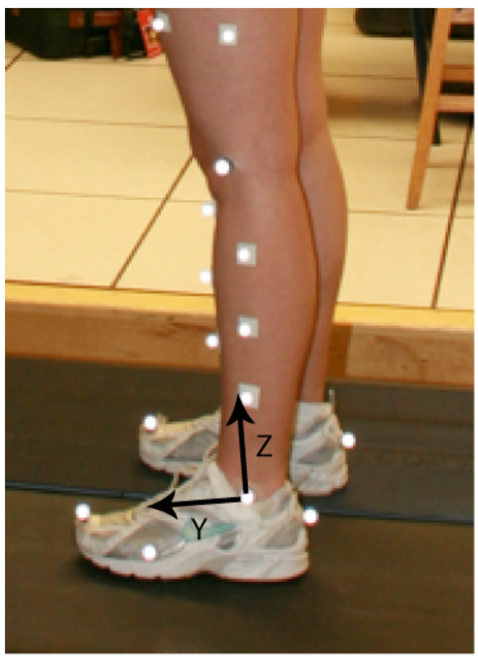


Figure 2.7: Shank-based coordinate system
This sagittal, shank-based coordinate system is defined by the direction of the Z-axis between the lateral malleolus and the lateral epicondyle.

Once we determined this shank-based coordinate system, we transformed the COP data into it according to Equation 2.1, where (x_T, y_T, z_T) are the transformed coordinates, R is a 3x3 rotation matrix, P is a 3x1 translation vector, and (x_0, y_0, z_0) are the initial coordinates. The final row, w, is not used in this application since the transformation does not include scaling. We then fit a circular arc to this transformed data using circle-fitting code from the MathWorks website (Buscher, 2004).

$$\begin{bmatrix} x_T \\ y_T \\ z_T \\ w \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} & & \\ & R & \\ & & \end{bmatrix} & \begin{bmatrix} \\ P \\ \\ \end{bmatrix} \\ 0 \quad 0 \quad 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} x_0 \\ y_0 \\ z_0 \\ 1 \end{bmatrix} \tag{2.1}$$

An example plot is shown below in (Figure 2.8). Upon inspection, we found that the data formed a cloud of points near the toe that did not follow the circular arc. Thus, we modified the algorithm to eliminate all data points after contralateral heel strike, as previous work suggested that the ankle-foot system did not create a rocker following contralateral heel strike (Hansen et al., 2004). Our data did not include forces for the right force plate so contralateral heel strike was approximated as the time when the right 2nd metatarsal reached its most anterior point. This modified process eliminated the extra data points near the toe, as seen in (Figure 2.9).

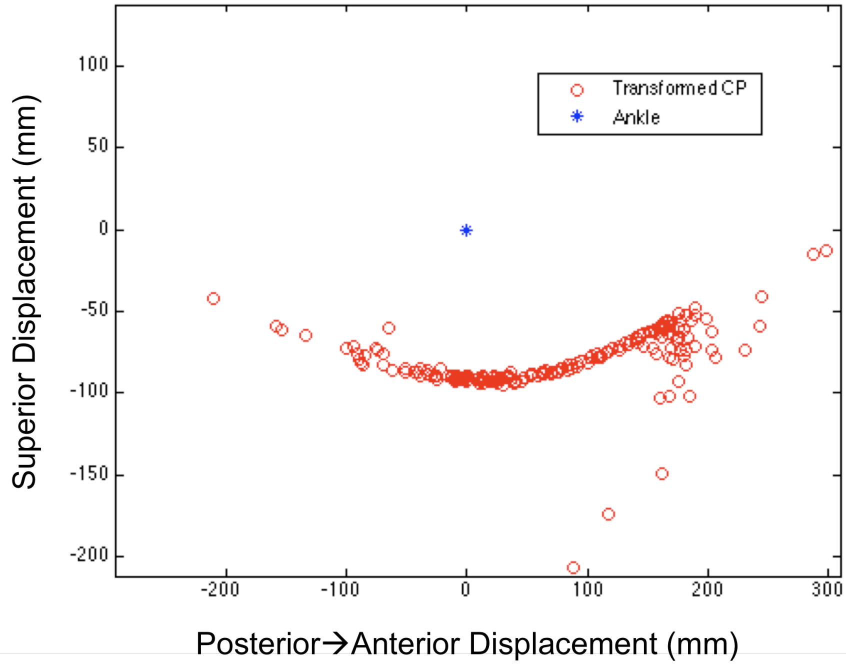


Figure 2.8: Ankle-foot roll over shape with cloud of data

The cloud of data on the far right is due to the decreased forces during double stance causing increased error

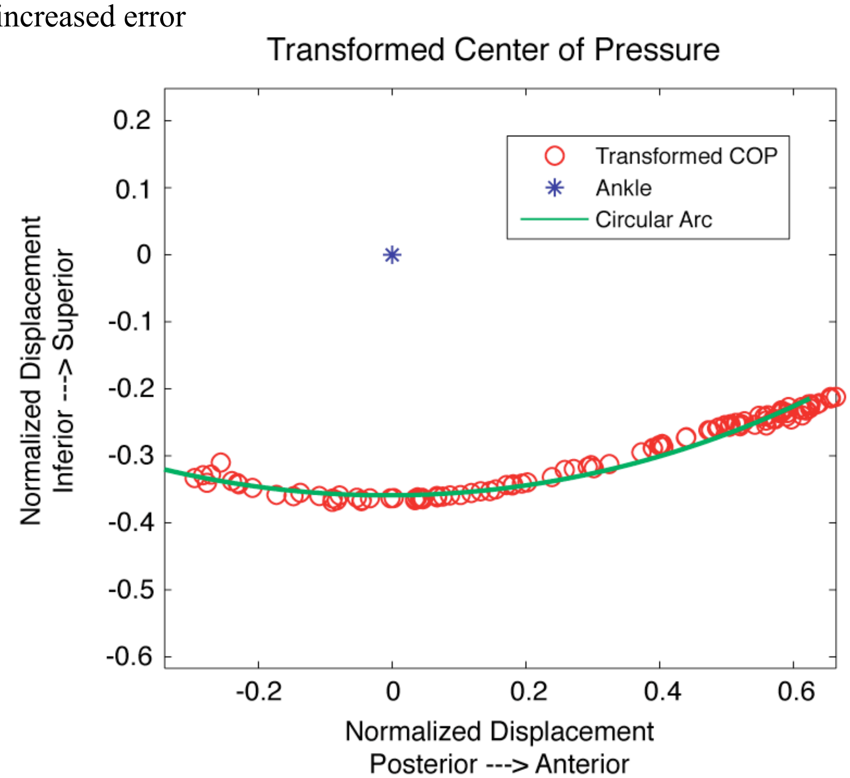


Figure 2.9: Roll-over shape (normalized by height) with truncated data

This roll-over shape has been truncated at contralateral heel strike to eliminate the error introduced during double stance

We found the radius and the location of the center of the circular arc fit to the transformed COP data. The anterior shift was defined as the y-displacement between the lateral malleolus and the center of the circle, with positive shift indicating a displacement along the positive y-axis toward the 2^{nd} metatarsus.

We analyzed the radius and anterior shift data, normalized by height, using a repeated measures analysis of variance (ANOVA) on seven cycles for each subject at each condition, since seven cycles was the maximum number of useable cycles for some subjects. Mauchly's test was used to verify sphericity and the Greenhouse-Geisser correction was applied if the sphericity assumption was violated. Statistical tests were performed using SPSS.

We subsequently performed two sets of post-hoc tests if the repeated measures ANOVA indicated significant changes. First, we compared the three levels of speed at constant levels of BWS and the four levels of body weight support at constant speeds using paired t-tests with the Bonferroni correction factor for multiple comparisons to account for the reduced degrees of freedom. The Bonferroni correction factor for these nine conditions required $p<0.006$ for significance. Second, we compared each combination of speed and BWS back to the baseline of 0% BWS, 100% SS speed. In this case, $p<0.005$ indicated significance due to the 11 comparisons we performed.

3. Results

Despite the findings of previous research that indicated the clinical invariance of the ankle-foot roll-over shape, we found that the shape did change with varied levels of speed and BWS during BWSTT. Both the radius and the anterior shift presented statistically significant changes.

3.1 Radius

The radius of the ankle-foot roll-over shape was affected significantly by speed ($p<.001$), BWS ($p<.001$), and the interaction of speed and BWS ($p<0.001$). The mean radii and standard deviations are presented in Table 3.1. Figure 3.1, below, shows a plot of mean radius varying with speed and BWS.

Table 3.1: Mean normalized radii (radius/height) at varied speeds and body weight support

	0% BWS	30% BWS	50% BWS	70% BWS
50% SS	0.183±0.051	0.191±0.057	0.190±0.047	0.182±0.066
100% SS	0.188±0.027	0.194±0.041	0.207±0.041	0.169±0.056
150% SS	0.187±0.039	0.184±0.055	0.160±0.069	0.135±0.069

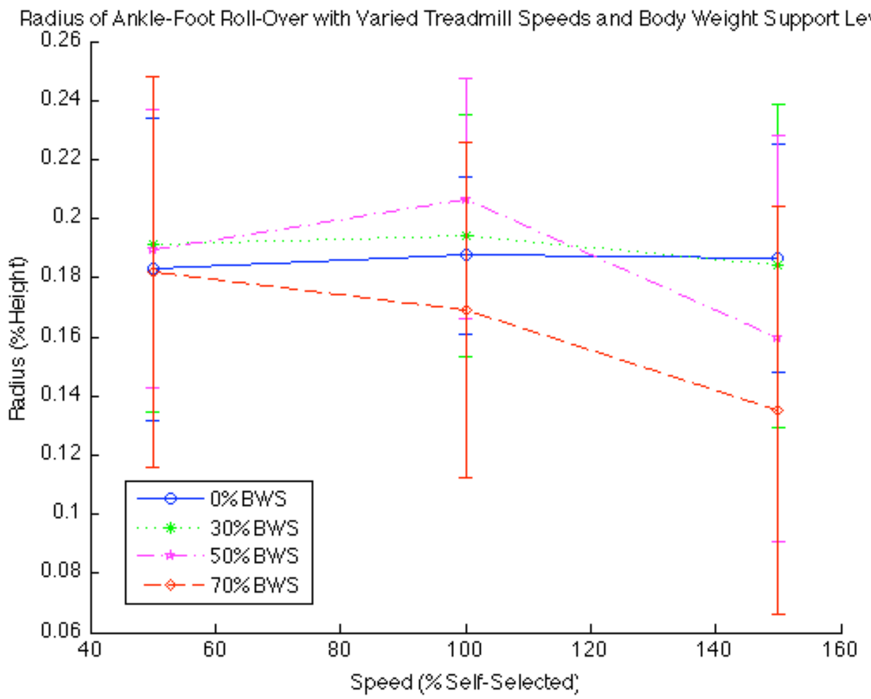


Figure 3.1: Normalized radius of the ankle-foot roll-over shape with varied speed and BWS
The radius ankle-foot roll-over shape is shown varied with speed and BWS with error bars representing standard deviation

Even though the radius changed significantly with speed and BWS, these changes did not result in any clear trends. As seen in Figure 3.2 and Figure 3.3, which show the mean radii for each subject with varied speeds and BWS, respectively, different subjects may have adapted to changed speeds and levels of BWS using different strategies. For instance, subjects 19, 20, 21, and 22 tended to increase radius with speed, 14 and 15 decreased radius with speed, and subject 13 increased and then decreased.

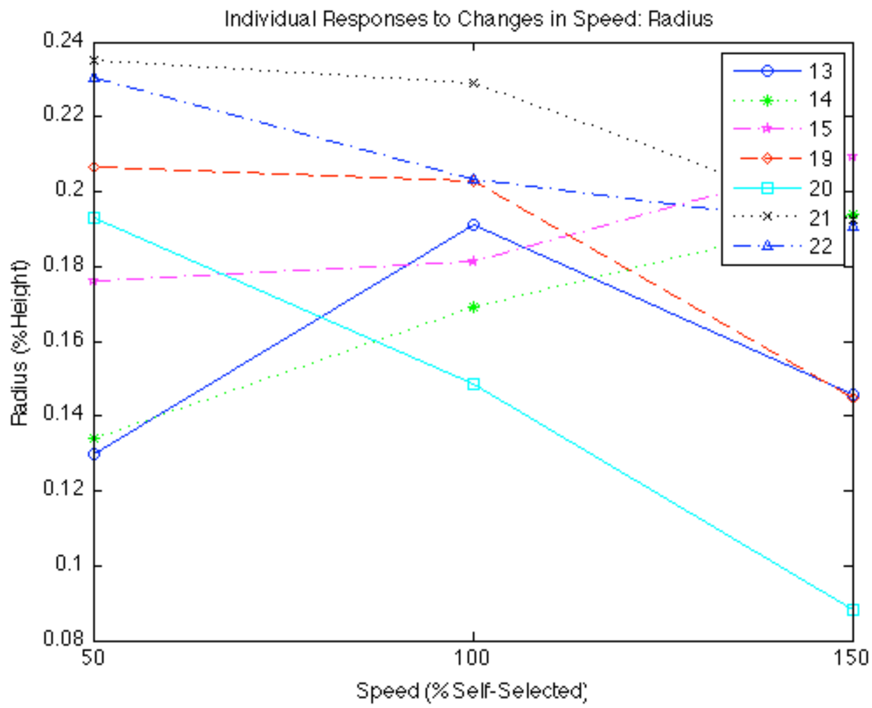


Figure 3.2: Individual subjects' normalized radii with increased speed

The individual subjects appeared to adapt differently to increases in speed as the data do not display any consistent trend

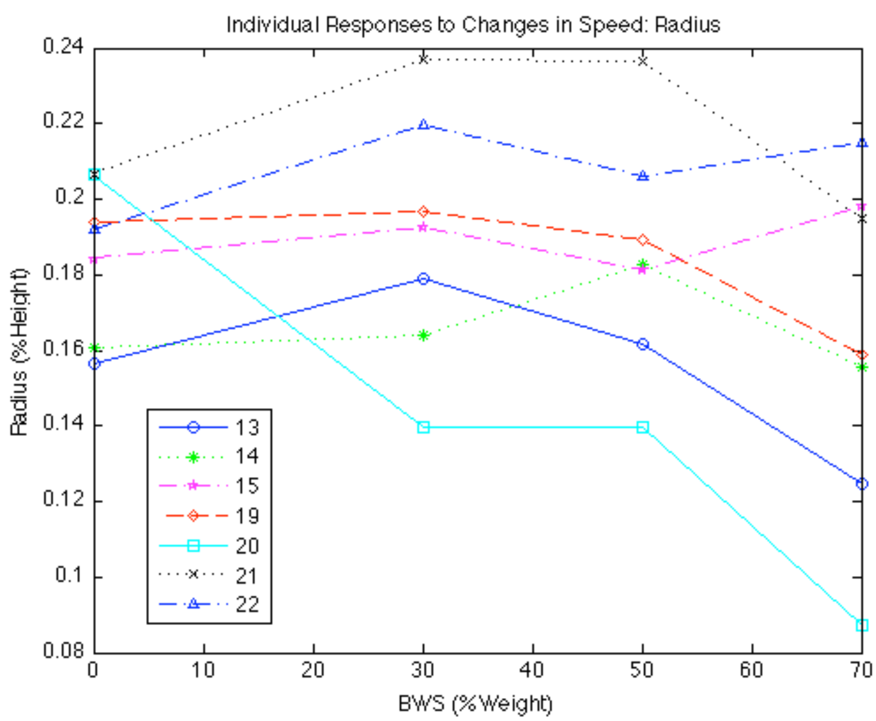


Figure 3.3: Each subjects' normalized radii with increased body weight support

The subjects appear to be using varying strategies to adapt to changes in body weight support.

As seen in Figure 3.4 and Table 3.2, the radius changed significantly between 50%SS speed and 150%SS speed (p=.001) and between 100%SS and 150%SS speeds (p<.001 for both). However, the radius did not change significantly between 50%SS and 100%SS speeds (p=0.480). Figure 3.5 and Table 3.3 show that the radius changed between 70% BWS and all other levels (p<0.001 for all) but not within 0%, 30%, and 50% BWS (p>0.242). Due to Bonferroni correction factors, significance for these comparisons occurred at p<0.006 (see Experimental Methods).

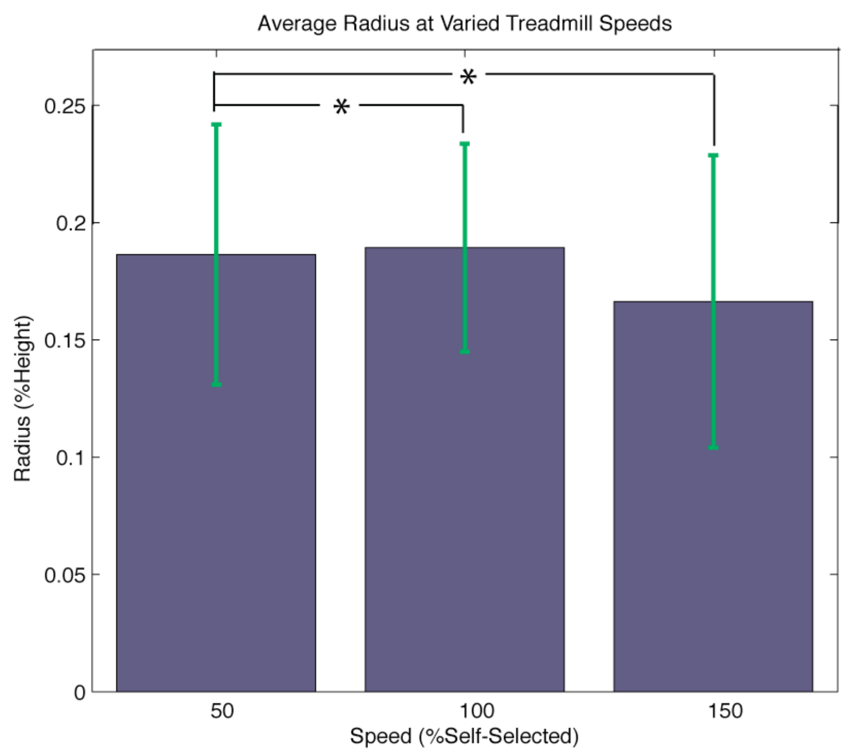


Figure 3.4: Average normalized radius with varied treadmill speed
The radius changed significantly between 150% SS speed and both other levels of speed. (*) indicates significance.

Table 3.2: Values of average normalized radius for varied speed

Speed (% SS)	50	100	150
Radius (%Height)	0.186±0.056	0.189±0.044	0.166±0.062

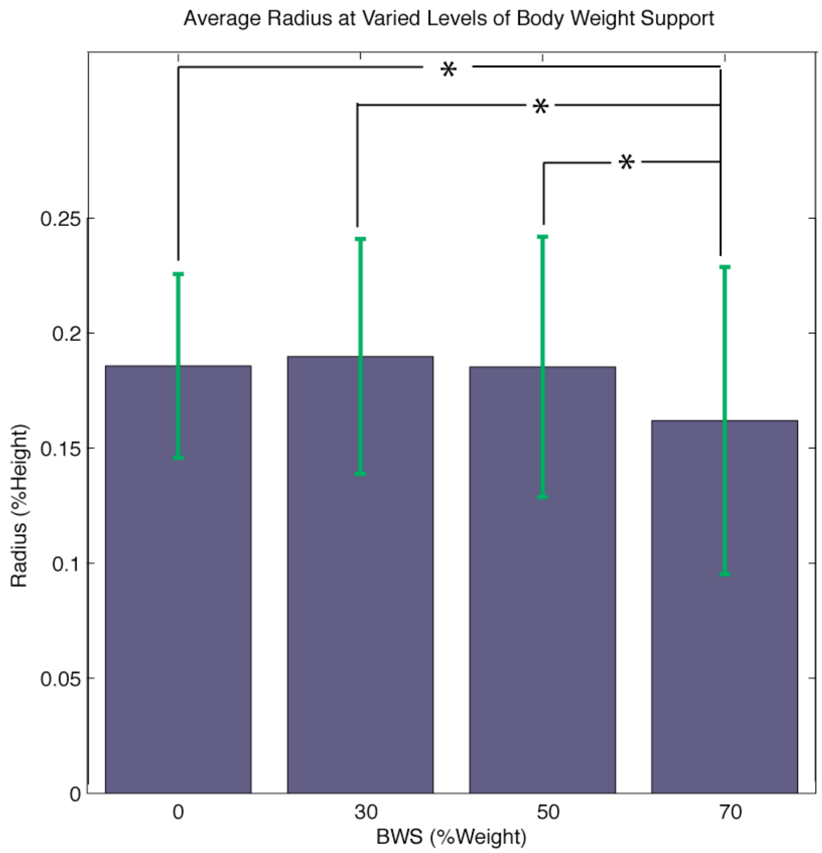


Figure 3.5: Average normalized radius with varied levels of BWS
The average radius changed significantly between 70%BWS and all other levels of BWS. (*) indicates significance.

Table 3.3: Values of average normalized radius with varied BWS

BWS (%Weight)	0	30	50	70
Radius (%Height)	0.186±0.040	0.190±0.051	0.185±0.057	0.162±0.067

Finally, Table 3.4 shows the changes between full weight bearing, no BWS and all other conditions. Only one condition, 150% self selected speed and 70% BWS, was significantly different from the baseline condition ($p<0.001$). Significance, due to Bonferroni correction factors, occurred at $p<0.005$ (see Experimental Methods, p.18).

Table 3.4: Comparison of normalized radius at all BWS and speed combinations back to baseline (shaded). (*) indicates significance.

		BWS (% Weight)			
		0	30	50	70
Speed (% SS)	50	0.183±0.051	0.191±0.057	0.190±0.047	0.182±0.066
	100	0.188±0.027	0.194±0.041	0.207±0.041	0.169±0.057
	150	0.187±0.039	0.184±0.055	0.160±0.069	0.135±0.069*

3.2 Anterior Shift

Speed (p=0.033), BWS (p=0.013), and the interaction of speed and BWS (p<0.001) significantly affected the anterior shift. Figure 3.6 below, shows a plot of mean anterior shift varying with speed and BWS. The mean anterior shifts and standard deviations are presented in Table 3.5.

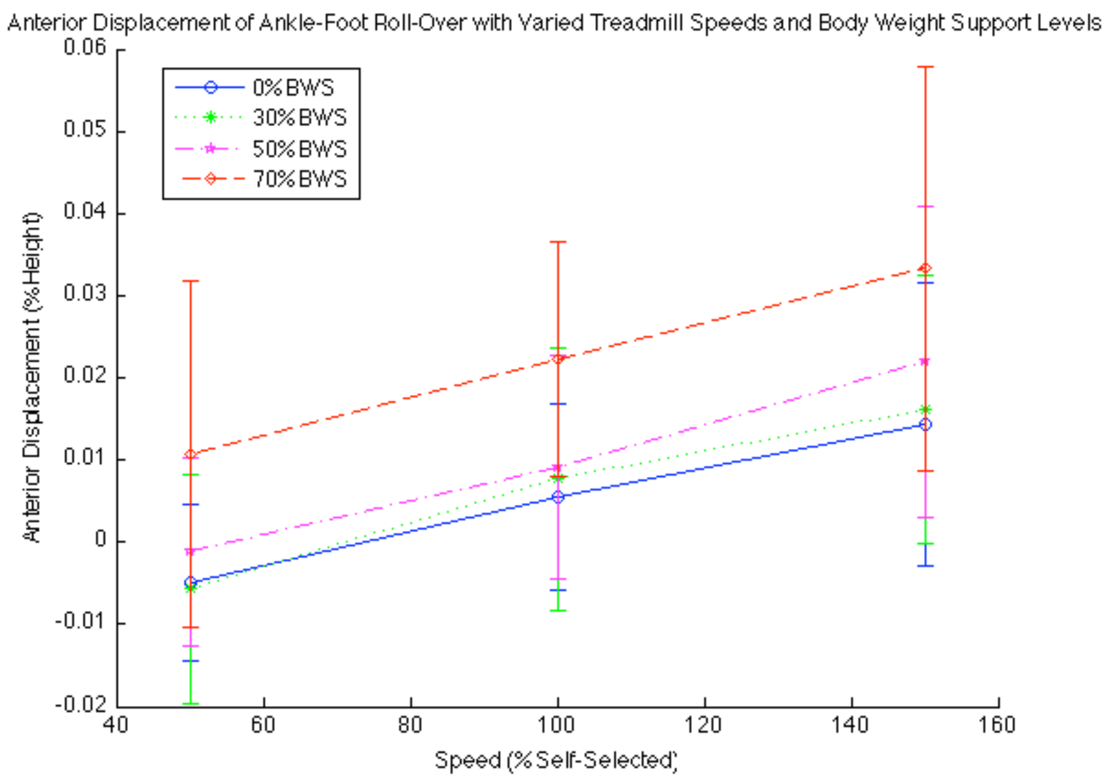


Figure 3.6: Normalized anterior shifts (anterior shift/height)
The anterior shift, normalized by height, as it varies with speed and body weight support. Error bars represent standard deviation.

Table 3.5: Normalized anterior shifts (anterior shift/height)

	0% BWS	30% BWS	50% BWS	70% BWS
50% SS	-0.005±0.010	-0.006±0.014	-0.001±0.012	0.011±0.021
100% SS	0.006±0.011	0.008±0.016	0.009±0.014	0.022±0.014
150% SS	0.014±0.017	0.016±0.016	0.022±0.019	0.033±0.025

As opposed to the radius, the anterior shift demonstrates a clear trend of increasing with increased speed and with increased body weight support. Unlike the radius, the individual trends for each subject follow similar patterns (Figure 3.7 and Figure 3.8).

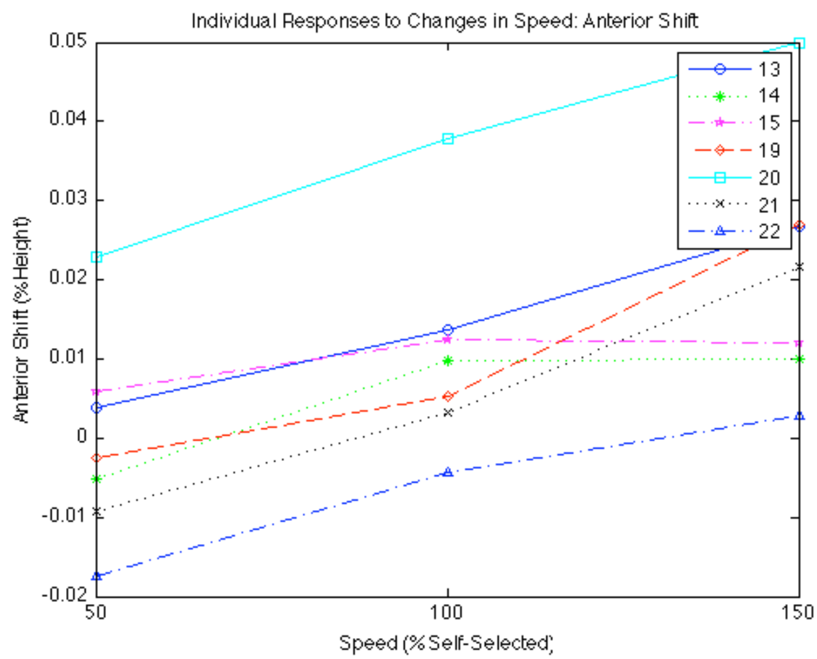


Figure 3.7: Each subject's normalized anterior shift in response to increased speed

Unlike the radius, the subjects appear to use similar strategies to adapt their anterior shift to increased speed.

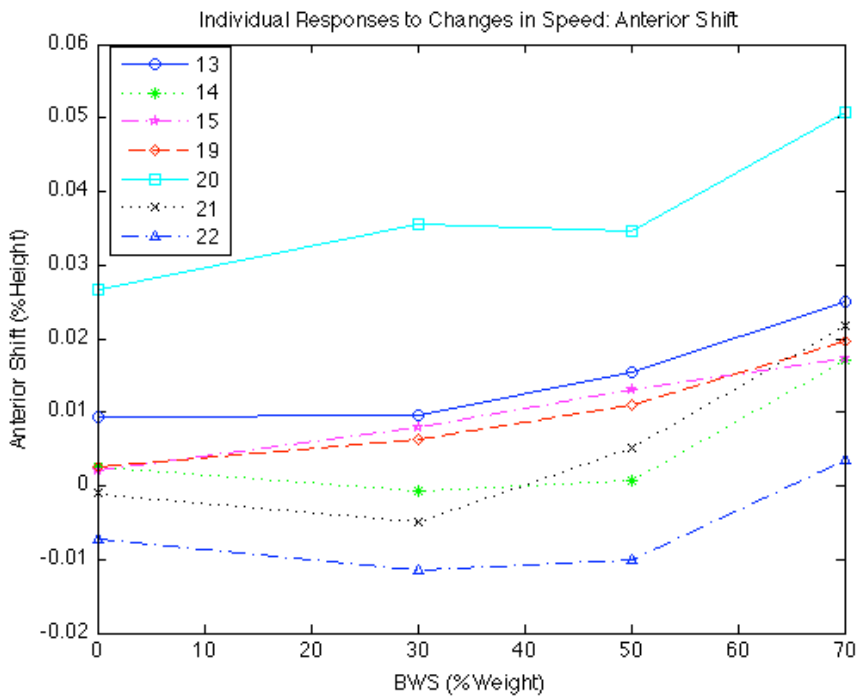


Figure 3.8: Each subject's normalized anterior shift in response to increased body weight support
The subjects appear to use similar strategies to adapt their radius to increased levels of body weight support

Figure 3.9 and Table 3.6 show that the anterior shift changed significantly between all speeds ($p<.001$). Figure 3.10 and Table 3.7 show that the anterior shift changed significantly ($p<.001$) for all levels of BWS except between 0% and 30% BWS ($p=0.247$). In both cases, significance occurred at $p<0.006$ (see Experimental Methods, p.18).

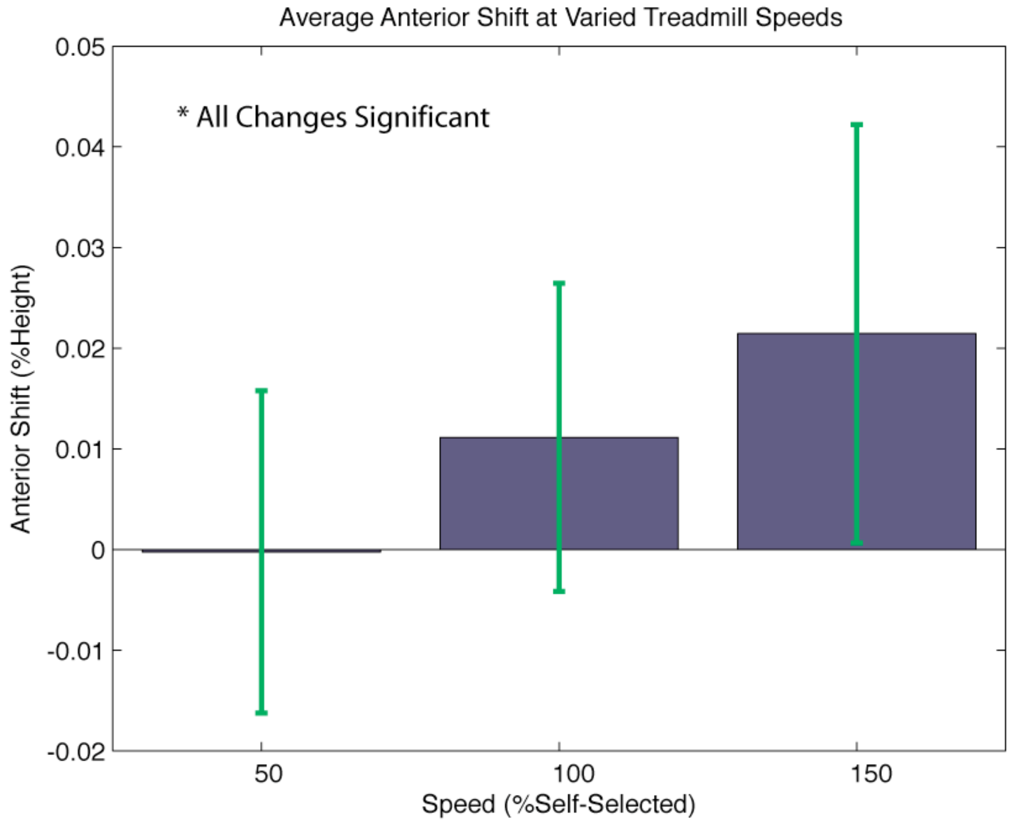


Figure 3.9: Average normalized anterior shift with varied levels of speed

The average anterior shift changed significantly between all speeds. Significance is not indicated graphically on the plot for clarity.

Table 3.6: Values of normalized anterior shift with varied speed

Speed (%SS)	50	100	150
Anterior Shift (%Height)	-0.0002±0.0160	0.0111±0.0153	0.0214±0.0208

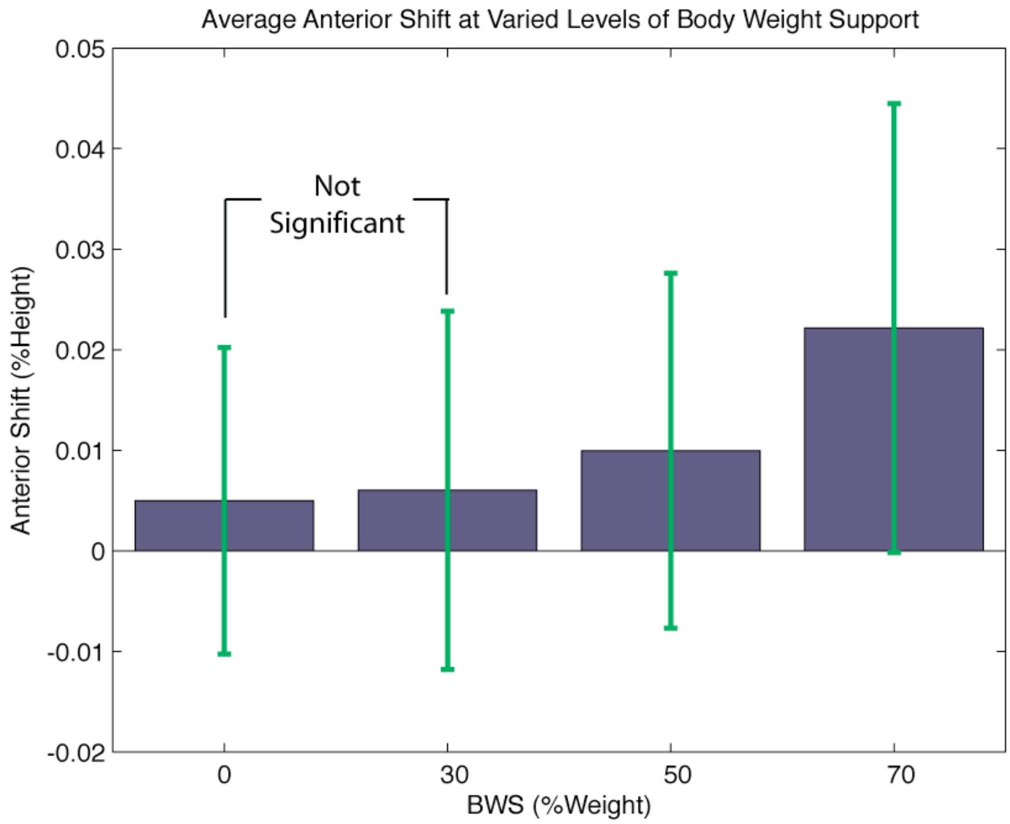


Figure 3.10: Average normalized anterior shift with varied levels of BWS
The average anterior shift changed significantly between all levels of BWS except between 0% and 30%. The only non-significant change is indicated on the plot.

Table 3.7: Values of normalized anterior shift with varied BWS

BWS (%Weight)	0	30	50	70
Anterior Shift (%Height)	0.0050±0.0152	0.0060±0.0178	0.0100±0.0177	0.0221±0.0223

Finally, as seen in Table 3.8, the anterior shift changed significantly ($p<=0.001$) between the baseline of 0% BWS and 100% SS speed and all conditions except for 50% SS speed with 70% BWS ($p=0.012$) and 100% SS speed and 30% BWS ($p=0.072$). Due to the Bonferroni correction factor, significance occurred at $p=0.004$ (see Experimental Methods, p.18).

Table 3.8: Comparison of normalized anterior shift at all combinations of BWS and speed back to the baseline condition (shaded). (*) indicates significance.

		BWS (% Weight)			
		0	30	50	70
Speed (%SS)	50	-0.0049±0.0095*	-0.0057±0.0140*	-0.0012±0.0115*	0.0108±0.00211
	100	0.0055±0.0113	0.0077±0.0160	0.0091±0.0136*	0.0224±0.0143*
	150	0.0144±0.0172*	0.0161±0.0164*	0.0219±0.0189*	0.0333±0.0247*

4. Discussion

Both the radius and the anterior shift changed significantly with speed, BWS, and the interaction of speed and BWS. This is in contrast to previous work indicating that the shape is clinically invariant during overground, unsupported walking (Hansen et al., 2004; Hansen et al., 2004; Hansen and Childress, 2005). The changes in radius did not exhibit any obvious trends, with each subject appearing to adapt differently to changes in BWS and speed. The anterior shift, however, increased steadily with increased speed and with increased BWS.

The radius changed significantly with speed and BWS, but was only significantly different from the baseline at the uppermost values of these parameters. It changed significantly between the highest speed, 150% SS, and all other speeds and between the highest level of BWS, 70%, and all other levels of BWS. The only condition that changed significantly from the baseline of 0% BWS and SS speed was that of 70% BWS and 150% SS speed. This indicates that, although the radius was changing within speed and BWS, the only change that caused the radius to significantly differ from normal walking conditions were these maximum speed and BWS levels.

The anterior shift changed between most speeds, between most levels of BWS, and between most conditions and the baseline. The shift tended to increase both with speed and with BWS. These results are consistent with previous work that found a small increase in forward shift with increased walking speed (Hansen et al., 2004) and a small increase in forward shift with speed when weight was added to subjects (Hansen and Childress, 2005). The results also correspond to previous findings that increased speed and BWS cause a decrease in percent stance and an increase in magnitude of peak dorsiflexion (Lathrop, 2009).

Additionally, previous modeling of asymmetrical gait for users of transtibial prostheses indicated that an anterior shift of the alignment of the prosthetic resulted in lower joint torques and increased stride lengths (Srinivasan et al., 2009). Similarly, our subjects may have adjusted their torques and stride lengths with increased BWS.

Even those changes that are statistically significant tended to occur at small percentages of the subjects' height. Hansen et al. suggested that an anterior shift of the roll-over shape center of less than 0.005H, where H is subject height, was not meaningful in a clinical setting (Hansen et al., 2004). However, our data demonstrate changes in both parameters between 0.01H and 0.03H. These changes may be clinically meaningful, but further work is necessary to determine the threshold beyond which changes in the roll-over shape are clinically relevant.

Since the roll-over shape is not constant in neurologically unaffected subjects, and since subjects appeared to use different strategies to adapt to changes in speed and BWS, it may not be possible to use the ankle-foot roll-over shape as an exact objective for training. However, it is not yet known whether SCI patients produce an ankle-foot roll-over shape similar to that of neurologically unaffected subjects. Since the variation of the shape exists at small percentages of height, if SCI patients early in training display a roll-over shape drastically different from neurologically unaffected subjects, it may be possible to use the roll-over shape to estimate a patients' rehabilitation progress using an envelope of observed shapes.

The change of both roll-over shape dimensions at the highest levels of body weight support and speed may indicate that it is not advisable to train patients at these extremes. If the ankle-foot roll-over shape is a measure of the interaction of forces and kinematics at the location of foot contact, this change from the baseline may mean that forces and kinematics are not being accurately replicated. Since it is important to replicate both forces and motions accurately in BWSTT, training under any conditions that do not accurately replicate normal gait may be detrimental to effective rehabilitation.

5. Conclusion

BWSTT is an effective therapy to help SCI patients regain the ability to walk. However, almost 25% of patients do not see significant improvement with the training, and those that do improve often have lingering gait abnormalities. Currently, the levels of BWS and speed used during the training are set based upon what “looks right” to the physical therapists. These parameters may affect the forces and motions experienced by the body during training. Since it is important to accurately match training forces and kinematics to those associated with normal gait, the purpose of this project was to determine the effect of speed and BWS on a metric combined forces and kinematics—the ankle-foot roll-over shape.

This ankle-foot roll-over shape has been suggested to be clinically invariant under a wide variety of walking conditions. However, we found that the key dimensions of this shape, the radius of its arc and the location of its center, varied across levels of BWS and speed. This variability was most pronounced at high values of each parameter.

5.1 Contributions

This research determined that the ankle-foot roll-over shape was not invariant with changes in BWS and speed. The radius of the shape changed significantly between 0% BWS, 100% SS speed and 70% BWS, 150% SS speed. The anterior shift of the center of the arc changed between nearly all combinations of BWS and speed. This indicates that the ankle-foot roll-over shape, which was previously suggested to be clinically invariant over varied walking conditions, obstacles, and added weight, is not invariant when the subject’s weight is supported.

This research determined that the ankle-foot roll-over shape cannot be considered an invariant metric during BWSTT. Thus, it may not be possible to use the ankle-foot roll-over shape as a means by which to evaluate the progress of a patient during rehabilitation. However, these changes were small (within a 5% of the subjects' height) so it may be possible to determine some bounds within which the roll-over shape would be considered "normal".

This research determined that the ankle-foot roll-over shape changed most drastically at the highest levels of BWS (70%) and speed (150% self-selected). Training at these levels may not be appropriate to accurately replicate the forces and motions associated with normal gait.

5.2 Additional Applications

Since we do not know how the ankle-foot roll-over shape varies in SCI patients, it is difficult to determine how useful the shape is as a clinical metric. A similar approach to what was done in this study should be applied to SCI patients to evaluate their response to variations in speed and BWS. These responses can then be compared back to the responses of the neurologically unaffected population

Additionally, the arc length of the roll-over shape may be calculated from this data. This arc length is a measure of how much of a person's effective rocker is being used (Hansen and Childress, 2005) and may be valuable as a measure of the rotation of the center of mass about a theoretical pivot on the ground (Gard and Childress, 2001).

Finally, the data should be analyzed to determine whether a shape similar to the ankle-foot roll-over shape exists in the frontal plane. If the ankle-foot roll-over shape is a measure of propulsion, a similar shape in the frontal plane could be a measure of stability. Since stability can be a problem for patients after rehabilitation, the existence of this shape could prove another useful measure of the interaction of forces and motion.

5.3 Future Work

Even though the ankle-foot roll-over shape is not an invariant metric with changes in BWS and speed, it may still be a useful outcome measure. Since the goal of training is to accurately reproduce the forces and kinematics present during normal gait, it may be that, during training, the patients work toward an appropriate roll-over shape. Future work should study the evolution of the ankle-foot roll-over shape throughout the recovery process for SCI patients. This progression would allow us to determine whether the shape converges to one set of parameters. If so, the converged set could be used as an outcome measure.

Additionally, this study determined that the ankle-foot roll-over shape changed with BWSTT parameters. However, it is still unknown what kinematic and kinetic changes cause this variation. Future work should determine these physical changes in order to discover if these changes in roll-over shape are related to the gait abnormalities that often persist after training. These relationships could then be used to inform more effective training.

5.4 Summary

The purpose of this study was to determine the effect of body weights support and speed on the ankle-foot roll-over shape during BWSTT. We tested 7 subjects at three speeds (50%, 100%, and 150% of self-selected speed) and four levels of BWS (0%, 30%, 50%, and 70% of body weight). We used motion capture and an instrumented treadmill to collect kinematic and force data, respectively. Custom MATLAB software calculated the ankle-foot roll-over shape and its characteristic variables, namely the radius of the arc and the location of its center. Although these characteristic variables have been suggested to be clinically invariant under most walking conditions, we found that the shape did vary across the speeds and levels of BWS. This variability was most prominent at the highest levels of speed and BWS. These results indicate that the ankle-foot roll-over shape, which is clinically invariant under full weight-bearing conditions may not be invariant when the subject's weight is partially supported.

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Appendix A: MATLAB Code

```
% This code provides the framework that allows the user to go from
% from the ASCII output from vicon to results.
clc;clear;

%% Set up Folders for Finding and Saving Data
% Ask for input for directory path
%folder = input('Enter Directory Path: ','s');
folder = '/Users/brooke/Documents/Research/Data and Code/New Research
Data';
save_folder = '/Users/brooke/Documents/Research/Data and Code/AFRO/';
today = datestr(now,30);
%today = '20091024T223854';
new_struct_directory = strcat(save_folder,'Struct/',today);
new_RONum_directory = strcat(save_folder,'Struct/',today);
mkdir(new_struct_directory);
%struct_save = '/Users/brooke/Documents/Research/Data and Code/Research
Data/StanceDataBWS19.mat';

%% Read in Data and Store in Structs
% Find folders contained in the directory of the form "BWSxx" and read
what
% is in them
folder_contents = dir(folder);
for i=1:length(folder_contents)
    if (folder_contents(i).isdir &&
strncmp(folder_contents(i).name,'BWS',3))
        check4digits = isstrprop(folder_contents(i).name, 'digit');
        if(check4digits(4) && check4digits(5) &&...
            length(folder_contents(i).name)==5)
            % pull out stance data

read_and_split(strcat(folder,'/',folder_contents(i).name),...

strcat(new_struct_directory,'/','StanceData',folder_contents(i).name));
        end
    end
end

%% Find Rollover Shapes
% Add in Find_rollover
subject_dir = dir(new_struct_directory);
k=1;
for i=1:length(subject_dir)
    if (strncmp(subject_dir(i).name,'StanceDataBWS',13))
        fprintf('%s',subject_dir(i).name)
        AFRO_Data.Subject(str2num(subject_dir(i).name(14:15))) =
Find_Rollover(strcat(new_struct_directory,'/',subject_dir(i).name));
        subject_list(k)=str2num(subject_dir(i).name(14:15));
        k=k+1;
    end
end

%% Add in Height and Trial Data
```

```
for i=1:length(subject_list)
    for k=1:length(AFRO_Data.Subject(subject_list(i)).trial)

AFRO_Data.Subject(subject_list(i)).Parameters(double(lower(AFRO_Data.Su
bject(subject_list(i)).trial(k).condition))-96)=k;
    end
end

for i=1:length(subject_list)
    run(strcat(folder,'/BWS',num2str(subject_list(i)),'/','Vitals.m'));
    AFRO_Data.Subject(subject_list(i)).Height = Height;
end

%% Normalize Thingers
for i=1:length(subject_list)
    for j=1:length(AFRO_Data.Subject(subject_list(i)).trial)
        for
k=1:length(AFRO_Data.Subject(subject_list(i)).trial(j).cycle)
            AFRO_Data.Subject(subject_list(i)).trial(j).cycle(k).rnorm
=...

AFRO_Data.Subject(subject_list(i)).trial(j).cycle(k).r/...
                AFRO_Data.Subject(subject_list(i)).Height;
            AFRO_Data.Subject(subject_list(i)).trial(j).cycle(k).ynorm
=...

AFRO_Data.Subject(subject_list(i)).trial(j).cycle(k).y/...
                AFRO_Data.Subject(subject_list(i)).Height;
            AFRO_Data.Subject(subject_list(i)).trial(j).cycle(k).znorm
=...

AFRO_Data.Subject(subject_list(i)).trial(j).cycle(k).z/...
                AFRO_Data.Subject(subject_list(i)).Height;
        end
    end
end

save(strcat(save_folder,'/',today),'AFRO_Data')

%% Output Data

conditions=[0.5 0
    0.5 30
    0.5 50
    0.5 70
    1 0
    1 30
    1 50
    1 70
    1.5 0
    1.5 30
    1.5 50
    1.5 70];

fid = fopen(strcat(save_folder,'/','r',today,'.csv'),'w');
if fid==-1
    fprintf('Could Not Open Save File. Check Permissions');
    break
```

```
end
fprintf(fid,'SubjectID,a,b,c,d,e,f,g,h,i,j,k,l\n');
% for i=1:length(subject_list)
%     for j=1:12
%         param = AFRO_Data.Subject(subject_list(i)).Parameters(j);
%         for
k=1:length(AFRO_Data.Subject(subject_list(i)).trial(param).cycle)
%             fprintf(fid,'%d,',subject_list(i));
%             fprintf(fid,'%f,%d,',conditions(j,1),conditions(j,2));
%             fprintf(fid,'%f,',AFRO_Data.Subject...
%                 (subject_list(i)).trial(param).cycle(k).rnorm);
%             fprintf(fid,'%f,',AFRO_Data.Subject...
%                 (subject_list(i)).trial(param).cycle(k).ynorm);
%             fprintf(fid,'%f',AFRO_Data.Subject...
%                 (subject_list(i)).trial(param).cycle(k).znorm);
%             fprintf(fid,'\n');
%         end
%     end
% end
for i=1:length(subject_list)
    for j=1:7
        fprintf(fid,'%d,',subject_list(i));
        for k=1:12
            param = AFRO_Data.Subject(subject_list(i)).Parameters(k);
            fprintf(fid,'%f,',AFRO_Data.Subject...
                (subject_list(i)).trial(param).cycle(j).rnorm);
        end
        fprintf(fid,'\n');
    end
end

fclose(fid);

fid = fopen(strcat(save_folder,'/','y',today,'.csv'),'w');
if fid==-1
    fprintf('Could Not Open Save File. Check Permissions');
    break
end
fprintf(fid,'SubjectID,a,b,c,d,e,f,g,h,i,j,k,l\n');
for i=1:length(subject_list)
    for j=1:7
        fprintf(fid,'%d,',subject_list(i));
        for k=1:12
            param = AFRO_Data.Subject(subject_list(i)).Parameters(k);
            fprintf(fid,'%f,',AFRO_Data.Subject...
                (subject_list(i)).trial(param).cycle(j).ynorm);
        end
        fprintf(fid,'\n');
    end
end

fclose(fid);

fid = fopen(strcat(save_folder,'/','z',today,'.csv'),'w');
if fid==-1
    fprintf('Could Not Open Save File. Check Permissions');
    break
end
```

```
fprintf(fid,'SubjectID,a,b,c,d,e,f,g,h,i,j,k,l\n');
for i=1:length(subject_list)
    for j=1:7
        fprintf(fid,'%d,',subject_list(i));
        for k=1:12
            param = AFRO_Data.Subject(subject_list(i)).Parameters(k);
            fprintf(fid,'%f,',AFRO_Data.Subject...
                (subject_list(i)).trial(param).cycle(j).znorm);
        end
        fprintf(fid,'\n');
    end
end

fclose(fid);
```

```
function []=read_and_split(file_directory,save_file_path)
% This file takes all of the files in from the testing data folder,
% removes the header info, splits them into gait cycles, and stores
% all of the data in a .mat file
%=====================================================================
====


file_list = dir(file_directory);
trial_number = 1;
for file_number=1:length(file_list)
    clear stance_data(trial_number)
    if strncmp(file_list(file_number).name,'.',1)==1
    elseif strncmp(file_list(file_number).name,'Vitals',6)
    else
        disp(file_list(file_number).name)
        file_path =
strcat(file_directory,'/',file_list(file_number).name);
        bulk_data_struct = create_data_struct(file_path);
        stance_data(trial_number) =
find_stance_cycles(bulk_data_struct);
%         stance_data(trial_number).condition =
bulk_data_struct.condition;
        trial_number = trial_number+1;
    end
end

save(save_file_path , 'stance_data')
```

```
function datastruct = create_data_struct(filename)

% This function reads in the data exported from the VICON software and
% creates a large struct containing all fields.
%
% Input Variables:
%   filename      CSV file from VICON
%
% Output Variables
%   datastruct    Struct contating data
```

```
% Open File
fid = fopen(filename);

i = 0;
% Loop through every line of the file to make sections headers happy
and
% idenfity section starts
while(~feof(fid))
    % Get line
    line = fgetl(fid);
    % Increment line counter
    i=i+1;

    % At line starting with "Decription:', read out the condition from
    % chacracter 15
    if(strncmp(line,'Description:',12))
        datastruct.condition = line(15);

    % Trajectory header location
    elseif(strncmp(line,'TRAJECTORIES', 12))
        % Mark start
        trajectories_start = i+1;

        fgetl(fid);
        i=i+1;

        % Correct and read header
        [trajectories_header1,trajectories_header2] =
process_header(fid);
        i=i+2;

        line = fgetl(fid);
        i=i+1;

        % Store width
        trajectories_width = length(findstr(line, ',')) + 1;

    % Analog data location
    elseif(strncmp(line,'ANALOG',6))
        % Mark start
        analog_start = i+1;

        fgetl(fid);
        i=i+1;

        % Correct and read header
        [analog_header1,analog_header2] = process_header(fid);
        i=i+2;

        line = fgetl(fid);
        i=i+1;

        % Store width
        analog_width = length(findstr(line, ',')) + 1;

    % Force plate data location
    elseif(strncmp(line,'FORCE PLATES',12))
```

```
        % Mark start
        force_start = i+6;

        % Skip ahead to header
        fgetl(fid);
        i=i+1;
        fgetl(fid);
        i=i+1;
        fgetl(fid);
        i=i+1;
        fgetl(fid);
        i=i+1;
        fgetl(fid);
        i=i+1;
        fgetl(fid);
        i=i+1;

        % Correct and read header
        [force_header1,force_header2] = process_header(fid);
        i=i+2;

        line = fgetl(fid);
        i=i+1;

        % Store width
        force_width = length(findstr(line, ',')) + 1;

    end
end

% Close file before csvread
fclose(fid);

% Read in the rest of the data past each header
data1 = csvread(filename,trajectories_start+2,0,[trajectories_start+2 0
analog_start-4 trajectories_width-1]);

% Read in the rest of the data past each header
data2 = csvread(filename,analog_start+2,0,[analog_start+2 0
force_start-9 analog_width-1]);

% Read in the rest of the data past each header
data3 = csvread(filename,force_start+2,0,[force_start+2 0 i-2
force_width-1]);


% Make a struct with the correct names, yay!
for i = 1:length(trajectories_header1)
    datastruct.data.(trajectories_header1{i}).(trajectories_header2{i})
= data1(:,i);
end
for i = 1:length(analog_header1)
    datastruct.data.(analog_header1{i}).(analog_header2{i}) =
data2(:,i);
end
for i = 1:length(force_header1)
    datastruct.data.(force_header1{i}).(force_header2{i}) = data3(:,i);
end
```

```
end

function [header_line1_processed,header_line2_processed] =
process_header(fid)
% This function reads in a pair of header lines from a section of the
VICON
% file, corrects for invalid characters, and fills in the categories to
% match 1:1 with the data labels.
%
% Input Variables:
%   fid                         File handle
%
% Output Variables
%   header_line1_processed      Header line containing categories
%   header_line2_processed      Header line containing data labels

    % Read in two header lines
    header_line1 = fgetl(fid);
    header_line2 = fgetl(fid);

    % Split header lines in to fields
    header_line2_processed = strread(header_line2, '%s', 'delimiter',
',');
    header_line1_processed = strread(header_line1, '%s', 'delimiter',
',');

    % Make header line 1 length match line 2 length
    while(length(header_line1_processed) <
length(header_line2_processed))
        header_line1_processed{length(header_line1_processed)+1} = '';
    end

    % Fill gaps in line 1
    count = 1;
    % Fix for missing first field
    if(isempty(header_line1_processed{1}))
        header_line1_processed{1} = 'Field #';
    end

    % Set initial category
    previous_title = header_line1_processed{1};

    % Make each empty category match the previous category
    for count = 1:length(header_line1_processed)
        if(isempty(header_line1_processed{count}))
            header_line1_processed{count} = previous_title;
        else
            previous_title = header_line1_processed{count};
        end
    end

    % Make field names appropriate
    header_line1_processed = kill_bad(header_line1_processed);

    % Make field names appropriate
    header_line2_processed = kill_bad(header_line2_processed);
end
```

```
function a = kill_bad(a)
% This function kills bad characters in the header lines that make
Matlab
% unhappy
%
% Input Variables:
%   a                           Input text
%
% Output Variables
%   a                           Output text

    for count = 1:length(a)
        a = strrep(a, '#', 'Num');
        a = strrep(a, '*', 'Star');
        a = strrep(a, ' ', '');
        a = strrep(a, ':','');
    end
end
```

```
function divided_gait = find_stance_cycles(bulk_data)

% This function takes a matrix of gait data and finds the gait
transitions.
% It considers the start of a gait cycle to be heel strike.
%
% Input Variables:
%   bulk_data      Struct generated by "Create_data_struct.m"
%
% Output Variables
%   divided_gait    Struct contating gait data separated by cycle
%
% Brooke Morin - Revised 10/11/08


% ====================== FIND HEEL STRIKES ===========================

in_spike = 0;
ncycle = 1;
heel_strike = zeros(1,8);

for i=1:length(bulk_data.data.ForceZ.N)
    if bulk_data.data.ForceZ.N(i)>100 && in_spike~=1
        n = i;
        while bulk_data.data.ForceZ.N(n)>25 && n>1
            n=n-1;
        end
        heel_strike(ncycle) = n;
        in_spike = 1;
    end
    if i>2 && in_spike == 1 && i<length(bulk_data.data.ForceZ.N)-1
        if bulk_data.data.RTOE.Y(i)>bulk_data.data.RTOE.Y(i-2)
            if bulk_data.data.RTOE.Y(i+2)<bulk_data.data.RTOE.Y(i)
                ohs(ncycle)=i;
            end
        end
    end
```

```
    if bulk_data.data.ForceZ.N(i)<25 && in_spike ==1
        toe_off(ncycle) = i;
        in_spike = 0;
        ncycle = ncycle+1;
    end


end



% ===================== CREATE NEW ARRAYS ============================

columns = fieldnames(bulk_data.data);

for i=1:ncycle-2
    for j = 1:length(columns)
        sub_columns = fieldnames(bulk_data.data.(columns{j}));
        for k = 1:length(sub_columns)
            divided_gait.cycle(i).(columns{j}).(sub_columns{k}) = ...

bulk_data.data.(columns{j}).(sub_columns{k})(heel_strike(i):ohs(i));
        end
    end

end
divided_gait.condition = bulk_data.condition;
```

```
function Subject_Data = Find_Rollover(bulk_data_location)
% Foot Rollover Practice
% Brooke Morin

jcf.knee = 57;
jcf.ankle = 37;
foot_length = 275;
height = 1677;

%
======================================================================
==
% Load and store data from file
%
======================================================================
==

% This first command reads in the raw marker data which is the second
% sheet in the sample data spreadsheet.
bulk_data = load(bulk_data_location);
rollover_struct = get_rollover_data(bulk_data);

 for trial_number = 1:length(rollover_struct)
    fprintf('%d:',trial_number)
%      for trial_number = [1]
real_cycle_number = 0;

    for cycle_number = 1:length(rollover_struct(trial_number).cycle)
```

```
        fprintf('%d,',cycle_number)

%         figure(1)

%   for cycle_number = [1:8]
        clear transformed

        data = rollover_struct(trial_number).cycle(cycle_number);
        if isempty(data.knee.x)
            disp('OH NO!')
        else
        real_cycle_number = real_cycle_number +1;


% ======================================================================
% Set up tranformation matrix
% ======================================================================

        for i = 1:length(data.knee.x)

% Create vectors to be used as coordinates
% Ankle to knee (Z-vector)
            location_vector_ANKtoKNE =
([data.knee.x(i),data.knee.y(i),data.knee.z(i)]-...
                [data.ankle.x(i),data.ankle.y(i),data.ankle.z(i)]);
            my_axes.z_hat(i,1:3) = location_vector_ANKtoKNE...
                ./norm(location_vector_ANKtoKNE);

% Heel to toe
% Temporary vector
            location_vector_HEELtoMET =
([data.toe.x(i),data.toe.y(i),data.toe.z(i)]-...
                [data.heel.x(i),data.heel.y(i),data.heel.z(i)]);
            my_axes.temp_hat(i,1:3) = location_vector_HEELtoMET...
                ./norm(location_vector_HEELtoMET);

% Create x-axis
            my_axes.x_hat(i,1:3) =
cross(my_axes.temp_hat(i,1:3),my_axes.z_hat(i,1:3))./...

norm(cross(my_axes.temp_hat(i,1:3),my_axes.z_hat(i,1:3)));

% Create y-axis
            my_axes.y_hat(i,1:3) =
cross(my_axes.z_hat(i,1:3),my_axes.x_hat(i,1:3))./...
                norm(cross(my_axes.z_hat(i,1:3),my_axes.x_hat(i,1:3)));

        end

% Transform points into new coordinate system
        for i = 1:length(data.knee.x)
            % Translation matrix
            translation_vector =
[data.ankle.x(i);data.ankle.y(i);data.ankle.z(i)];
            % Translation and rotation
            transformation_matrix =
inv([my_axes.x_hat(i,1:3)',my_axes.y_hat(i,1:3)',my_axes.z_hat(i,1:3)',
...
```

```
                translation_vector;0,0,0,1]);
            % Transformed Center of pressure
            % 1 = x, 2 = y, 3 = z
            transformed.COP(1:4,i) =
transformation_matrix*[data.COP.x(i);data.COP.y(i);0;1];
            % Ankle too!
            transformed.ankle(1:4,i) =
transformation_matrix*[data.ankle.x(i);data.ankle.y(i);data.ankle.z(i);
1];
        end
%         hold on
%         plot(transformed.COP(2,:),transformed.COP(3,:),'bd')
%         axis equal

       %plot(transformed.COP(2,:),transformed.COP(3,:),'*')
        % A hack at removing outliers.
        points_to_kill = ones(length(transformed.COP(2,:)));
        for i = 1:length(transformed.COP(2,:))
            friend_count = 0;
            for j = 1:length(transformed.COP(2,:))
                if(sqrt((transformed.COP(2,i)-transformed.COP(2,j))^2
+...
                        (transformed.COP(3,i)-transformed.COP(3,j))^2)
< 15) &&...
                        j~=i
                    friend_count = friend_count+1;
                end
            end
            if friend_count > 2
                points_to_kill(i) = 0;
            end
        end

        for i = length(points_to_kill):-1:1
            if(points_to_kill(i) == 1)
                transformed.COP(:,i) = [];
            end
        end

        % Fit circle to transformed shape
        [sagittal(trial_number).y0(cycle_number) ...
            sagittal(trial_number).z0(cycle_number) ...
            sagittal(trial_number).radius(cycle_number)] ...
            = circfit(transformed.COP(2,:)',transformed.COP(3,:)');

        r = sagittal(trial_number).radius(cycle_number);
%         if r>500
%             plot(transformed.COP(2,:),transformed.COP(3,:),'g*')
%         end
%         hold off
        circ_y = [-0.3*299:.01:.55*299];
        circ_z = -sqrt(r^2-(circ_y-
sagittal(trial_number).y0(cycle_number)).^2)+...
            sagittal(trial_number).z0(cycle_number);
% % ----------------------------------------------------------------
% % Plotting
%       figure(cycle_number)
% hold on
```

```
%
plot(transformed.COP(2,:)/height,transformed.COP(3,:)/height,'ro',trans
formed.ankle(3,2)/height,transformed.ankle(3,3)/height,'*',...
%      'markersize',8,'linewidth',1)
% plot(circ_y/height,circ_z/height,'g-','linewidth',2)
% hold off
% legend('Transformed COP','Ankle','Circular Arc')
% axis equal
% %-------------------------------------------------------------------

    Subject_Data.trial(trial_number).cycle(real_cycle_number).r = r;
    Subject_Data.trial(trial_number).cycle(real_cycle_number).y =...
        sagittal(trial_number).y0(cycle_number);
    Subject_Data.trial(trial_number).cycle(real_cycle_number).z =...
        sagittal(trial_number).z0(cycle_number);
    Subject_Data.trial(trial_number).condition =
bulk_data.stance_data(trial_number).condition;
end
    end
     fprintf('\n')
 end
```

```
 function rollover_struct = get_rollover_data(stance_bulk_struct)

%------------------------------------------------------------------
This code draws out the important markers from the kinematic data
% ----------------------------------------------------------------

stance_struct = stance_bulk_struct.stance_data;
for i=1:length(stance_struct)
    for j = 1:length(stance_struct(i).cycle)

rollover_struct(i).cycle(j).knee.x = stance_struct(i).cycle(j).LKNE.X;
rollover_struct(i).cycle(j).knee.y = stance_struct(i).cycle(j).LKNE.Y;
rollover_struct(i).cycle(j).knee.z = stance_struct(i).cycle(j).LKNE.Z;

rollover_struct(i).cycle(j).ankle.x = stance_struct(i).cycle(j).LANK.X;
rollover_struct(i).cycle(j).ankle.y = stance_struct(i).cycle(j).LANK.Y;
rollover_struct(i).cycle(j).ankle.z = stance_struct(i).cycle(j).LANK.Z;

rollover_struct(i).cycle(j).heel.x = stance_struct(i).cycle(j).LHEE.X;
rollover_struct(i).cycle(j).heel.y = stance_struct(i).cycle(j).LHEE.Y;
rollover_struct(i).cycle(j).heel.z = stance_struct(i).cycle(j).LHEE.Z;

rollover_struct(i).cycle(j).toe.x = stance_struct(i).cycle(j).LTOE.X;
rollover_struct(i).cycle(j).toe.y = stance_struct(i).cycle(j).LTOE.Y;
rollover_struct(i).cycle(j).toe.z = stance_struct(i).cycle(j).LTOE.Z;

rollover_struct(i).cycle(j).COP.x = stance_struct(i).cycle(j).COPX.mm;
rollover_struct(i).cycle(j).COP.y = stance_struct(i).cycle(j).COPY.mm;

    end
end
```